Strategies for Reactive Power Control in Wind Farms with STATCOM

Francisco Díaz González[1], Marcela Martínez-Rojas[2], Andreas Sumper[12], Oriol Gomis-Bellmunt[12], Lluís Trilla[1]

[1]IREC Catalonia Institute for Energy Research

Josep Pla 2, B3, ground floor. 08019 Barcelona, Spain. Tel: +34 933560980

[2]Centre d'Innovaciò Tecnològica en Convertidors Estàtics i Accionaments (CITCEA-UPC)

E.U d'Enginyeria Tècnica Industrial de Barcelona - Dept. Ingeniería Eléctrica

C/ Comte d'Urgell, 187. 08036 Barcelona, Spain. Tel: +34 934137432

e-mail: fdiazg@irec.cat, marcela.martinez@citcea.upc.edu, sumper@citcea.upc.edu, gomis@citcea.upc.edu

Abstract. This paper presents three strategies for reactive power control in wind farms with STATCOM. First, the STATCOM system and its applications in electric power systems and wind farms are shown. Second, the modeling done of the wind farm, the STATCOM and the network are presented. Finally, control strategies for reactive power delivered by the park to the network when required are shown. The result of the implementation of each control strategy is shown by simulation.

Key words

Wind farm, reactive power control, DFIG.

1 Introduction

Wind energy has experienced a great increase in the last few decades. Currently, in the European Union there are 34 gigawatts of installed capacity in wind farms. This represents more than 5 times the installed power 20 years ago. The technology has evolved significantly while the cost of power generated has decreased. The objective of the EEC in 2020 is to achieve 12% of all energy produced from the wind power. This development rises from a global need for cleaner energy and a more away from fossil fuels. The ratio of greenhouse gases emitted by a wind farm, both onshore and offshore, are around $10-30 kgCO2/MWh$ of energy. In plants using fossil fuels the greenhouse gas ratio is around $400-500 kgCO2/MWh$ of energy [1]. The growing importance of wind power in the current energy system depends on structural and legislative changes in the energy sector, increased environmental awareness, and technological development of wind power generation systems and their integration into the electricity grid.

Technological development in the wind power field is an important challenge for its evolution. The fluctuation of wind causes fluctuations in the power delivered by the wind farm to the electricity network. Therefore, the development of systems to improve voltage stability, frequency stability and power quality [13] is an important line of research in the wind power field. The incorporation of Doubly Feed Induction Generators (DFIG generators) in wind turbines, improves stability and frequency of the voltage through their decoupled control of active and reactive power. However, the power delivered by the wind farm to the electricity network presents many defects. Below are some of them:

- Flicker, which is understood to be the sensation that is experienced by humans when subjected to changes in illumination intensity. The human maximum sensitivity to illumination changes is a frequency range between $5Hz$ to $15Hz$. The fluctuating illumination is caused by amplitude modulation of the feeding alternating voltage. It is particularly important in weaker grids. Wind variations cause power variations [13],[4].
- Frequency fluctuations due to power fluctuations.
- Harmonic emission due to the presence of electronic power converters in wind turbines.
- Voltage fluctuations due to aerodynamic aspects of wind turbines [3].

In order to promote the integration of wind farms into the electrical network, Flexible AC Transmission Systems, FACTS, are widely used. The FACTS STATCOM system is one of them. Numerous studies have shown that transient and steady state stability can be improved by controlling the voltage of the connection point of the wind farm to the

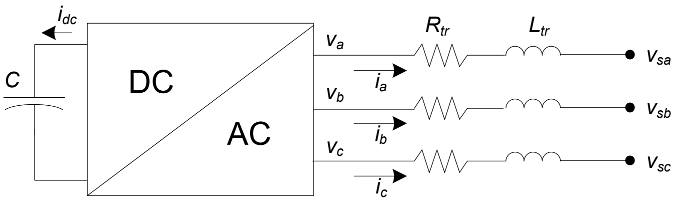


Figure 1: STATCOM description

network, [7]. The STATCOM system stimulates voltage stability by reactive power regulation. STATCOM provides or absorbs reactive power to or from the grid to compensate small voltage variations at the connection point of the wind farm with the grid. STATCOM is also used when a voltage dip occurs. Many studies show that STATCOM helps the wind farm to stabilize voltage especially after a voltage dip occurs [10].

Compared with other reactive compensation systems such as shunt capacitors, FACTS systems are more expensive. In [15] a comparative table is presented. In this table we can observe that the cost of a shunt capacitor is $8\$/kVAr$, while the cost of the STATCOM is $50\$/kVAr$. Nevertheless, FACTS systems provide faster and smoother response to changes in wind farm voltage. On the other hand, shunt capacitors give a poor response and it is not possible to control voltage on its point connection to the wind farm [14]. Compared with other FACTS systems connected in parallel with the generation system such as FACTS SVC [4], it is possible to guarantee that both are similar on their reactive compensation capacity. The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point. However, STATCOM is a bit more expensive.

STATCOM systems have been introduced in many applications. In [12], a $\pm 100MVAr$ STATCOM is installed in a $161kV$ distribution line. The function of STATCOM here is to respond quickly to maintain the voltage at a certain threshold level, preventing voltage collapse in situations of voltage disturbances. In [11], a $\pm 80MVAr$ STATCOM is installed to improve the power transmission capacity of the distribution line. In [4] STATCOM is used to mitigate the effect of flicker. In [16] a $\pm 50MVAr$ STATCOM is installed in a $220kV$ substation to improve the stability and the power transmission capacity of the distribution line. In [9] STATCOM is used to solve power quality problems on transmission lines. In [8], the benefits of installing a STATCOM in a wind farm to improve the behavior of the park when facing fault ride through situations. In [5] the benefits of installing a STATCOM in a wind farm to improve the stability and the power quality are shown. In [3], the positive effect of STATCOM to mitigate distortions in the energy supplied by the wind farm caused by the aerodynamics of wind turbines is studied.

In this paper we show various control strategies for reactive power delivered by a wind farm, which has a STATCOM system. This is considered a 9-bus model network, a wind farm model consists of DFIG generators and a model of STATCOM. Numerous dynamic simulations are shown.

2 STATCOM description

According to the IEEE, STATCOM system is a static synchronous generator operated as a static compensator connected in parallel whose output current (inductive or capacitive) can be controlled independently of the AC system voltage.

A charged capacitor acts as a source of direct current. This current feeds an AC/DC power converter, which produces a set of outputs with controllable three-phase voltages. Also, the frequency of these voltages is the AC system frequency. The AC/DC power converter is controlled by PWM techniques, so the output voltages achieved are practically sinusoidal. These controllers are possible by the high switching frequency of the IGBT, GTO, IGCT or IEGT transistors of the power converter [17]. The system connects to the grid via a transformer, Figure 1.

The system is characterized by a rapid response time and its ability to provide a control voltage to the connection point through reactive power compensation. It can be used for filtering harmonics, improving transient and dynamic stability, dynamic over voltages and under voltages, voltage collapse, steady state voltage, excess reactive power flow and undesirable power flow [6]. This enables that the wind farm, for instance, to have a better response in voltage dips as well as more stable system.

Usually, STATCOM is installed at the MV bus in the wind farm. Its aim is to help the wind farm in situations of voltage dips, voltage regulation, power factor control and power flow stabilizing.

3 STATCOM modeling

The operating principle of STATCOM is as follows:

- If $v = v_s$ (pu values), no current flows through R_{tr} and L_{tr}.

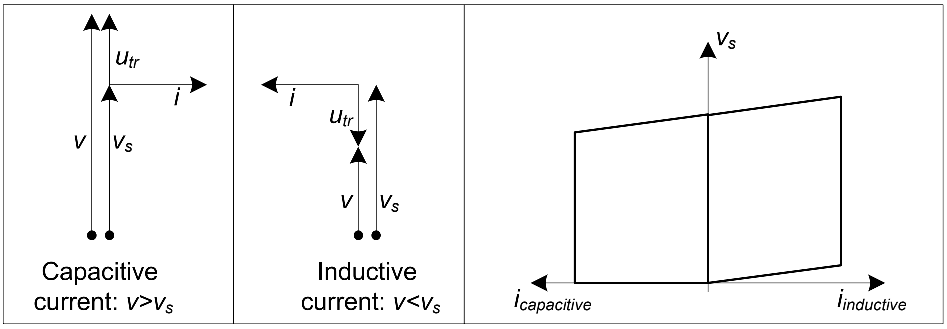


Figure 2: Operating principle and operation area of STATCOM

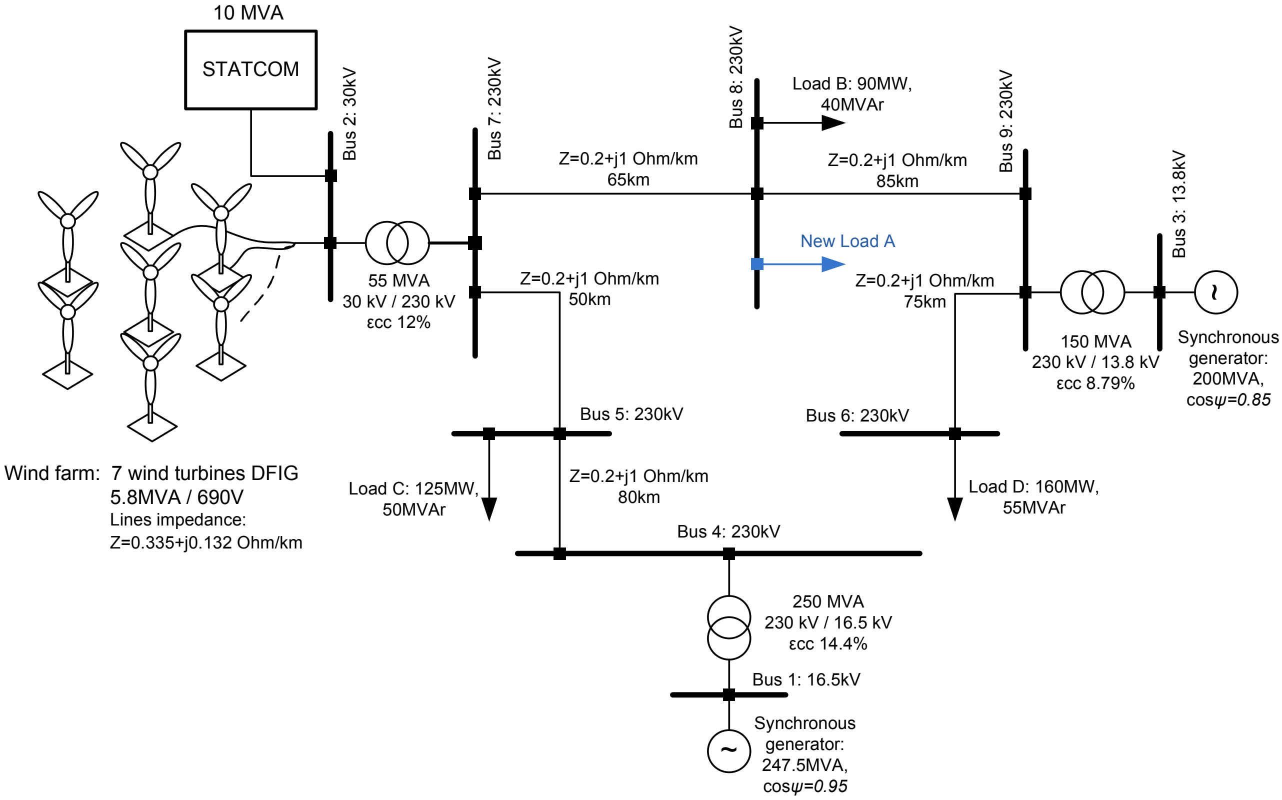


Figure 3: System description

- If $v > v_s$, current flows through R_{tr} and L_{tr}. As the impedance is essentially inductive, the current phasor is perpendicular to v_s and v voltages. STATCOM injects reactive current to the grid (capacitive current).
- If $v < v_s$, current flows through R_{tr} and L_{tr}. This time the current flow is opposite to the previous, which implies that STATCOM absorbs reactive power from the grid (inductive current).

Figure 2 shows a summary of the operating principle exposed. Inductive or capacitive currents appear according to the module of v and v_s voltages.

STATCOM reactive current is determined by the difference between grid voltage and power converter voltage. Reactive current is independent of the voltage of the connection point of STATCOM and is limited by the capacity of the power converter and grid voltage variation. The operation area of STATCOM is determined in Figure 2. The maximum inductive current is not assumed until a certain lower limit of the voltage. This is because the voltage drop across the coupling transformer.

4 System description

With DIgSILENT software [2], a 9-bus network with synchronous generators, various loads and a $41MVA$ wind farm which has a $10MVA$ STATCOM has been modeled. Figure 3 shows the overall scheme.

The characteristic parameters of STATCOM, DFIG generators and wind turbines are as follows:

Table 1: Characteristics parameters of STATCOM

Parameter	Value
Rating power	$10MVA$
Phase voltage	$30kV$
Transformer voltages	$30kV/3.3kV$
Transformer short circuit voltage	10%
Capacitor	$7000uF$

Table 2: Characteristics parameters of DFIG and wind turbine

Parameter	Value
Rating power	$5.8MVA$
Stator voltage	$0.69kV$
Rotor side dc voltage	$1.15kV$
Stator resistance R_s	$0.002929p.u.$
Stator reactance X_s	$0.125p.u.$
Magnetizing reactance X_m	$2.5p.u.$
Number of pole pairs	2
Connection	Y
Blade radius	$50m$
Rotor inertia of turbine	$6.1 \cdot 10^6 kg{\cdot}mm^2$
Shaft stiffness	$83 \cdot 10^6 Nm/rad$
Shaft torsional damping	$1.4 \cdot 10^6 Nms/rad$
Nominal turbine speed	$18rpm$

5 Strategies for reactive power control

The aim is to show the performance of STATCOM, DFIG generators and the network during a voltage fluctuation at one point of the grid. To do this, at a specified time a $60MVAr$ new load has been connected to the network. The introduction of this new load causes a sharp drop in the voltage in all buses of the network.

In order to compensate this voltage fluctuation the wind farm can provides reactive power. The reactive power referenced by the wind farm control is proportional to the voltage deviation at the connection point of the wind farm about a constant set point. The demand for this power can be supplied by the generators or by the STATCOM. Accordingly, we present the following control strategies:

- STATCOM is the only element of the park that delivers reactive power, wind turbines are working with a unity power factor.
- A proportional dispatch of reactive power between wind turbines and STATCOM.
- Wind turbines deliver reactive power when the STATCOM system reaches its maximum capacity.

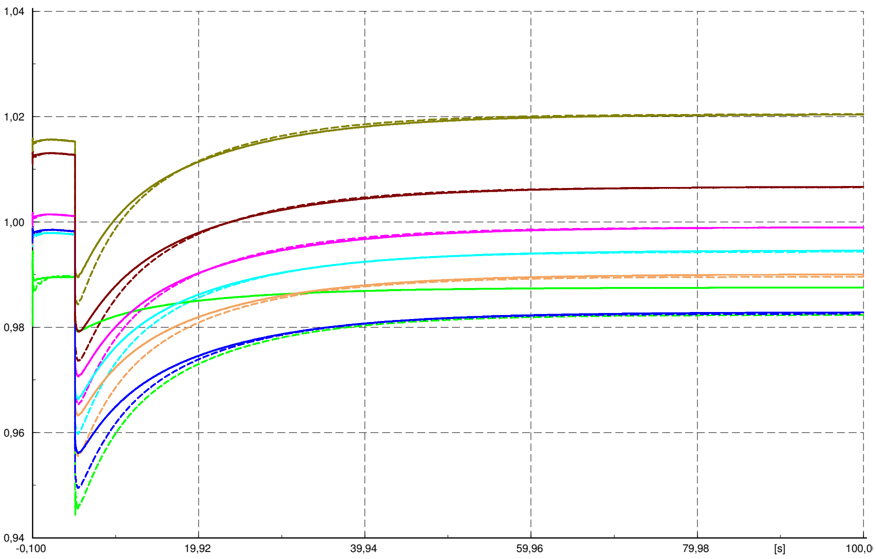
5.1 STATCOM is the only element of the park that delivers reactive power, wind turbines are working with a unity power factor

The introduction of a new $60MVAr$ reactive load in the system causes a sudden voltage drop at its buses. It has a demand for reactive power proportional to voltage deviation experienced by the bus where the wind farm is connected. This reactive power is referenced to local control of STATCOM. Figure 4 shows that the STATCOM reactive power helps to raise the voltage level during the transition caused by the introduction of the new load on the system.

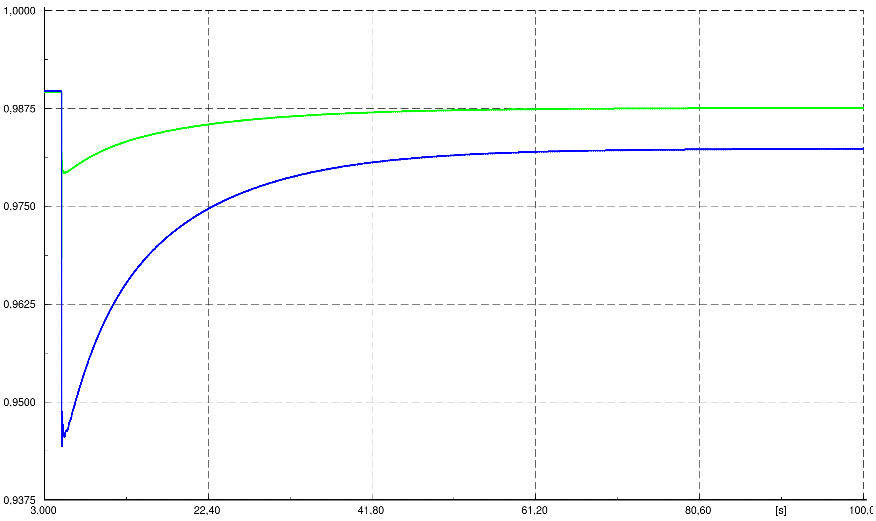
At the wind farm connection point there is greater compensation. In particular, the provision of reactive power helps to reduce the deviation of bus voltage level from $0.946p.u.$ (in a situation where there is no supply of reactive power) to $0.979p.u.$

This contribution of reactive power has implications for the voltages and currents of the turbines, as shown in Figure 5. Voltage and current peaks are significantly damped.

Figure 6 shows the reactive power supplied by STATCOM. It is observed at the initial instant of the transient, delivering approximately $10MVAr$.



(a) In solid lines are plotted the system voltages (pu values) with injection of STATCOM reactive power. In dashed lines are plotted the system voltages (pu values) with no injection of STATCOM reactive power. Green lines: wind farm bus



(b) Voltage (pu values) at wind farm connection point with (green line) and without (blue line) reactive power injection of STATCOM

Figure 4: Voltage with and without reactive power injection of STATCOM

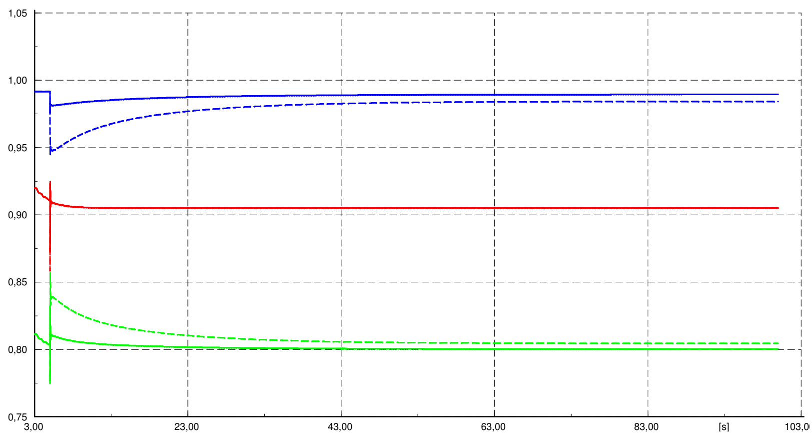


Figure 5: In solid lines are plotted the wind turbine generators magnitudes with injection of STATCOM reactive power to the system. In dashed lines are plotted the wind turbine generators magnitudes with no injection of STATCOM reactive power. In blue lines the stator generator voltages are shown (pu values). In red lines the active power of the generators are shown (pu values). In green lines the stator generator currents are shown (pu values).

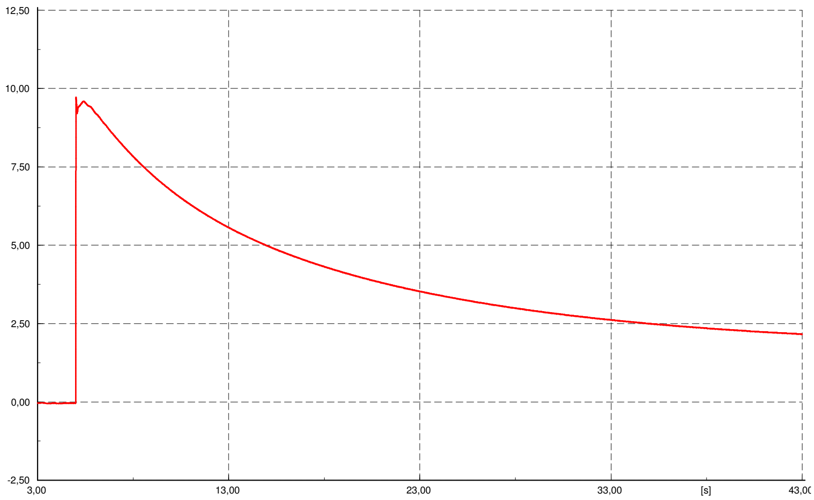


Figure 6: STATCOM reactive power in $MVAr$

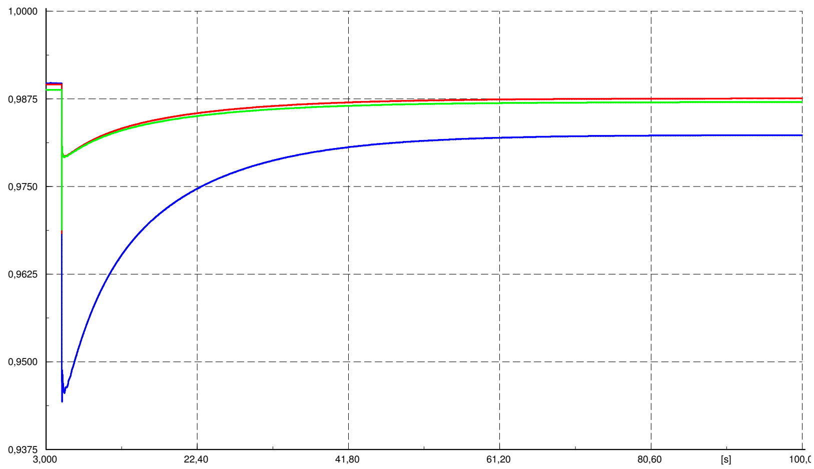


Figure 7: Voltage at wind farm connection point. In blue line the voltage with no reactive power injection is shown (pu values). In red line the voltage with reactive power injection of STATCOM is shown (pu values). In green line the voltage with proportional dispatch of reactive power between STATCOM and wind turbines is shown (pu values).

5.2 A proportional dispatch of reactive power between wind turbines and STATCOM

In this strategy, a proportional dispatch of reactive power between STATCOM and turbines is performed. The dispatch function D is:

$$D = \frac{Q^{required}}{Q^{maxST} + \sum_{k=1}^{n} Q^{maxWT}} \tag{1}$$

$$Q^{*}_{ST} = D{\cdot}Q^{maxST} \tag{2}$$

$$Q^{*}_{WT} = D{\cdot}Q^{maxWT} \tag{3}$$

Thus, wind turbines and STATCOM receive a reactive power reference that depends on total demand and the capacity of each element.

The reactive power delivered as a whole is the same as in the previous case, thus the voltage of the system buses do not have a different behavior. Figure 7 shows the voltage at the connection point of the wind farm. Shows the curves that correspond to the situations described above.

However, voltage and current of DFIG generators experience a change from the previous strategy (Figure 8). Make a reactive power control of the generators helps to keep their voltage levels, since practically does not suffer a significant variation during the transient caused by the connection of new load to the system. Delivered active power is also suffering only a minor variation, but the stator currents are significantly higher due to the reactive current injected.

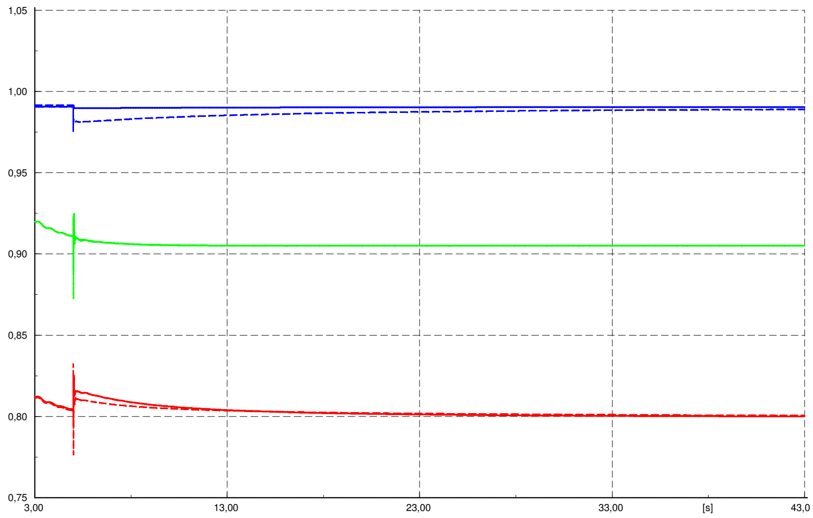


Figure 8: In solid lines are plotted the wind turbine generators magnitudes with proportional dispatch of reactive power between STATCOM and wind turbines. In dashed lines are plotted the wind turbines generators system voltages with injection of STATCOM reactive power. In blue lines the stator generator voltages are shown (pu values). In red lines the active power of the generators are shown (pu values). In green lines the stator generator currents are shown (pu values)

5.3 Wind turbines deliver reactive power when the STATCOM system reaches its maximum capacity

In this case, a new $100MVAr$ load has been introduced on the system. Thus, the lowering of the voltage in the system buses is higher than in the previous cases. Therefore, the reactive power to be supplied by the wind farm to the network is greater than $10MVAr$ for several seconds. During this time, the STATCOM is delivering its maximum power ($10MVAr$) and the mills meet the remaining demand. Figure 9 shows the voltage of the bus 2 when there is no supply of reactive power, and when the turbines and STATCOM inject reactive power according to the explained strategy.

As shown, all buses experience a slighter decrease on their voltage level when a new load is introduced in the system. Specifically, the bus that experiences a lower deviation is the one that the wind farm is connected to. When the new load is connected, STATCOM and the turbines provide reactive power, allowing a voltage level decrease of only $0.9783p.u.$ This voltage level is much higher than in the case of an absence of reactive power compensation, $0.9182p.u.$

After a few seconds, as reactive power demand drops STATCOM can supply all the demand. The turbines reactive power reference is now $Q^{WT} = 0$. Figure 10 shows the reactive power provided by STATCOM and a wind turbine in both situations.

As noted, the contribution of reactive power by STATCOM not only helps to restore voltage at the wind farm connection point, but it helps at all system buses. The system is more stable. This can be seen in the PV curves.

6 Voltage stability: PV curves

Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance. PV diagrams are an essential tool for analyzing the voltage stability of power systems. PV curves are generated by increasing the active power of one load or of a certain number of loads by keeping the power factor constant. The loads are increased until the load flow doesn't converge any more. In this case, variations in the load A Bus 8 are applied. Initially a $10MW$ load with 0.85 power factor is considered. As the system approaches the maximum loading point or voltage collapse point, both real and reactive power losses increase rapidly. This phenomenon can be seen from the plots, commonly referred to as P-V curve. The maximum load that the system can be supplied before entering to the collapse point or nose point is called loading margin (LM). Figures 11 and 12 show PV curves for bus system where there are loads, and the bus which is connected wind farm. It can be seen as the loading margin of all buses is increased to 4.5% of its value in a situation where there is no reactive power compensation by wind farm.

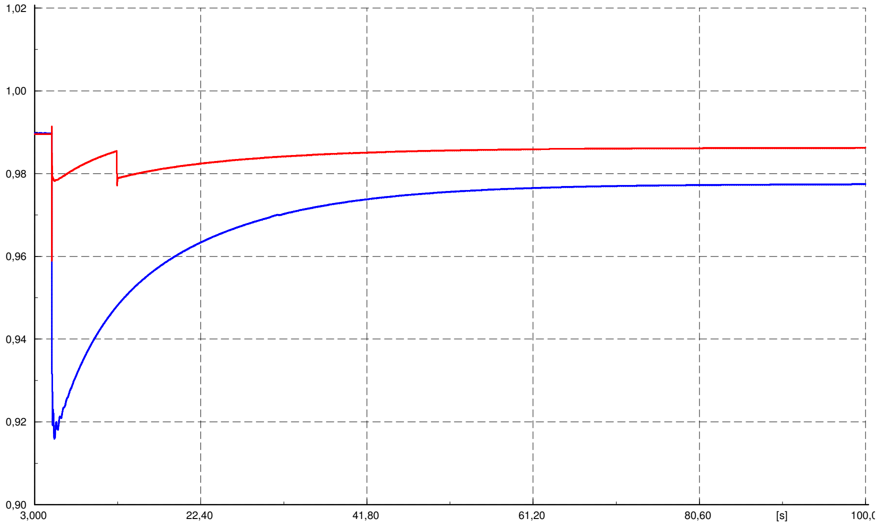


Figure 9: Voltage at wind farm connection point with no reactive power injection (blue line, pu values) and with reactive power injection by STATCOM and wind turbines (red line, pu values).

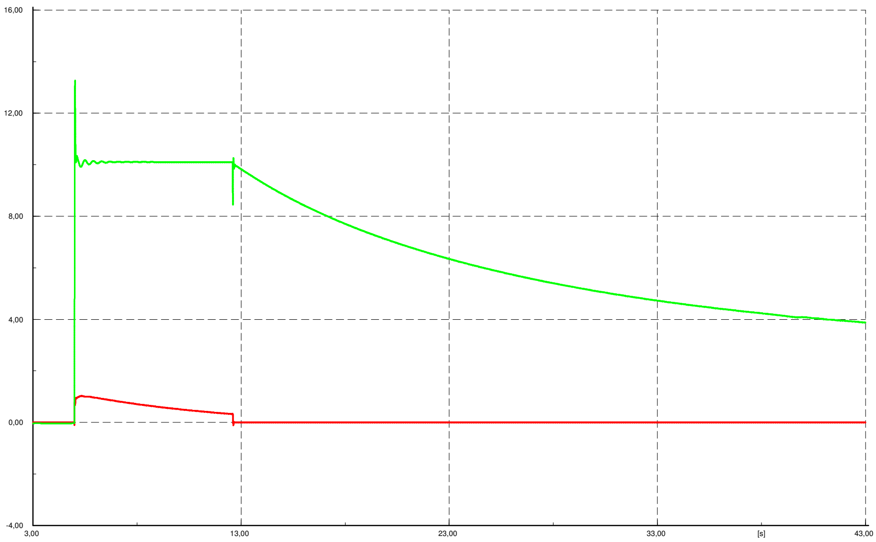


Figure 10: Reactive power injected to the grid by STATCOM (green line, in $MVAr$) and wind turbines (red line, in $MVAr$)

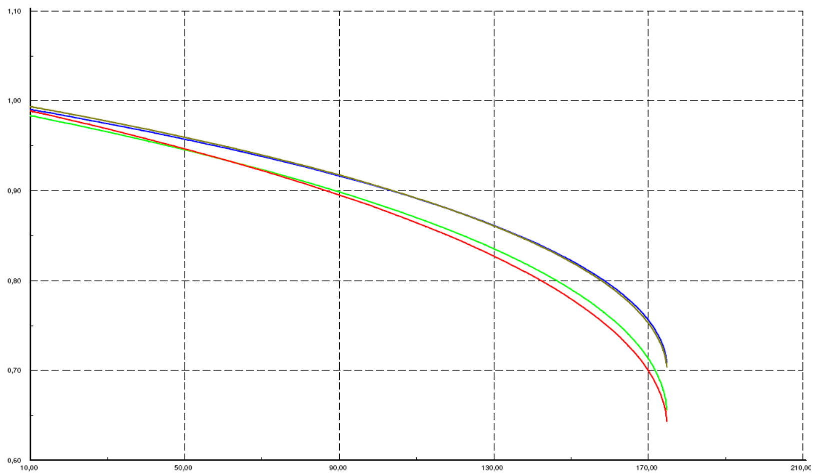


Figure 11: P-V curves. With no reactive power injection of STATCOM. x-axis, power in MW. y-axis, voltage in $p.u.values$

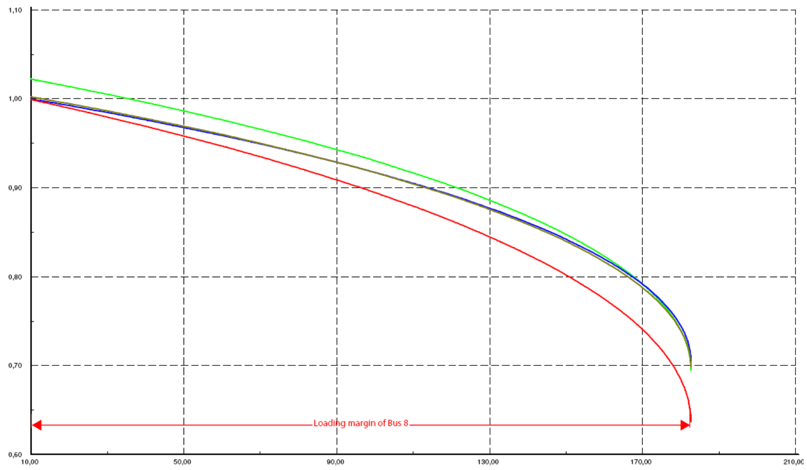


Figure 12: P-V curves. With reactive power injection of STATCOM. x-axis, power in MW. y-axis, voltage in $p.u.values$

7 Conclusions

This paper presents three strategies for reactive power control in wind farms with STATCOM. A 9-bus network with synchronous generators, various loads and a wind farm which has a STATCOM has been modeled. A new purely reactive load has been connected on the system to cause a voltage fluctuation at all system buses. Three strategies for STATCOM and wind turbines reactive power control have been considered to compensate this sudden voltage drop. The first of these strategies consists on wind turbines working with a unity power factor while STATCOM delivers its reactive power to the grid. In the others two strategies STATCOM and the wind turbines assume the demand of reactive power. If wind turbines inject reactive power, they suffer a lower voltage drop at their connection point, but their stator currents are higher due to the injection of reactive current. Future work will evaluate the losses in generators and in the park due to the increased current. PV curves have been plotted to study the effect on voltage stability of the reactive power added to the network by STATCOM. It has been shown that loading margin (LM) in the system buses improves significantly.

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